Switchable dual-wavelength Q-switched and mode-locked fiber lasers using a large-angle tilted fiber grating

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Abstract: We proposed and demonstrated pulsed fiber lasers Q-switched and mode-locked by using a large-angle tilted fiber grating, for the first time to our best knowledge. Owing to the unique polarization properties of the large-angle tilted fiber grating (LA-TFG), i.e. polarization-dependent loss and polarization-mode splitting, switchable dual-wavelength Q-switched and mode-locked pulses have been achieved with short and long cavities, respectively. For the mode-locking case, the laser was under the operation of nanosecond rectangular pulses, due to the peak-power clamping effect. With the increasing pump power, the durations of both single- and dual-wavelength rectangular pulses increase. It was also found that each filtered wavelength of the dual-wavelength rectangular pulse corresponds to an individual nanosecond rectangular pulse by employing a tunable bandpass filter.

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References and links


1. Introduction

Optical pulses with long pulse durations in the nanosecond to millisecond regime are required for many applications, including material processing [1], distance measurements, and remote sensing [2]. Q-switched lasers can deliver long pulses with high pulse energies and lower repetition rate (kHz) [3]. Although Q-switching can be implemented by either active or passive modulation, passively Q-switched fiber lasers are inherently more attractive as they can provide the desired Q-switched output without the need for external modulation [4, 5]. From a practical point of view, development of all-fiber Q-switched fiber lasers is the popular modern trend [6], and it is very desirable to implement multi-wavelength and wavelength-switchable pulsed laser [7, 8]. A dual-wavelength Q-switched fiber laser with a wavelength spacing of 0.2 nm based on graphene saturable absorber (SA) was reported, by using a fiber Bragg grating with two reflection peaks [9]. Benefiting from the birefringence-induced filtering effect, a dual-wavelength Q-switched fiber laser with a graphene SA has also been reported [10].

Besides Q-switched fiber lasers, there has been growing interest in the fact that nanosecond rather than picosecond or femtosecond pulses could also be realized by virtue of peak-power clamping effect in passively mode-locked fiber lasers with extended cavity length. Nanosecond square pulse generation in passively mode-locked fiber lasers was firstly
reported with amplifying Sagnac switch by Richardson [11] and nonlinear polarization rotation (NPR) by Matsas [12], respectively. Henceforth, various nanosecond square-wave fiber lasers with different cavity conditions have been demonstrated, such as nanosecond square-profile dissipative soliton laser with all-normal dispersion [13, 14], high-energy square-wave pulse laser with large net anomalous dispersion [15], and dissipative soliton resonance lasers [16–18]. We noted that the most rectangular pulse fiber lasers were under single wavelength operation. Regarding the wavelength versatility of the nanosecond mode-locked lasers, a dual-wavelength rectangular pulse ytterbium-doped fiber laser by using a microfiber-based graphene SA was demonstrated [19]. The dual-wavelength switchable operation was also achieved. However, the operation wavelengths and wavelength spacing are subjected to the intra-cavity random birefringence.

Tilted fiber gratings (TFGs), as a special category of fiber gratings, which are capable of coupling the core mode into both radiation modes and cladding modes, possess unique polarization spectrum characteristics [20–23]. This type of gratings generally involves three regimes according to the tilted angle, i.e. < 45°, = 45° and > 45°. 45°-tilted fiber grating (45°-TFG), which taps out the s-light and propagates the p-light based on the Brewster’s law, has been used as a new type of in-fiber polarizer for mode-locking [24–26]. Large-angle TFG (LA-TFG) with tilted angle >45°, featuring forward-propagating operation and strong polarization dependence [27], has been proposed as fiber sensors for strain [28], twist [29], loading [30], refractive index (RI) and liquid level [27, 31].

For the first time to our best knowledge, in this work we proposed and demonstrated a novel kind of pulsed fiber laser, which was Q-switched or mode-locked by using an LA-TFG. The polarization dependence of the LA-TFG can induce NPR effect in the laser cavity, and furthermore polarization-mode splitting enables polarization spectrum filtering. Thus, switchable dual-wavelength Q-switched and mode-locked pulses have been achieved with short and long cavities, respectively. Moreover, the mode-locked laser worked under the generation of nanosecond rectangular pulses, due to the peak-power clamping effect. With the increasing pump power, the durations of single- and dual-wavelength rectangular pulses broaden.

2. Fabrication and characterization of the LA-TFG

The LA-TFG was inscribed in H₂-loaded standard telecom fiber (SMF-28) by use of a frequency-doubled Ar + laser and the scanning mask technique. A commercial amplitude mask (from Edmund Optics Ltd) with a period of 6.6 μm was utilized for the LA-TFG inscription. Owing to the limited size of the amplitude mask, the effective exposure length of the fiber is only ~12 mm. During the inscription process, the amplitude mask was tilted at ~73° to induce in-fiber fringes blazed at ~78° [32]. The spectra of the fabricated 78°-TFGs were examined by use of the broadband light source combined with a polarizer and a polarization controller. The typical measured transmission spectrum of an LA-TFG shows a
series of dual-peak resonances in the wavelength range from 1200 nm to 1700 nm with a nearly even separation between adjacent resonances, as shown in the inset of Fig. 1. The zoomed one paired peaks at wavelength of 1554.9 nm and 1561 nm is shown in Fig. 1. When the light is polarized, either the equivalent fast- or the slow-axis mode can be fully excited or eliminated. The blue dotted line indicates the fast-axis mode, while the dashed red line shows the slow-axis mode. The full strength of the loss peak reached ~10 dB when it was fully excited. The black solid curve illustrates excitation of the two modes with un-polarized light. It can be seen that the fabricated LA-TFG features polarization-dependence and polarization-mode splitting.

3. Experimental set-up and results

![Fig. 2. Schematic of pulsed fiber laser with an LA-TFG (Q-switching without DSF, mode-locking with DSF).](image)

The schematic of the pulsed erbium-doped fiber laser with an LA-TFG is shown in Fig. 2. The laser consists of 1 m erbium-doped fiber (EDF) with nominal absorption coefficient of ~80 dB/m at 1530 nm and normal dispersion $\beta_2 = 66.1$ ps$^2$/km. The EDF is pumped through a 980/1550 wavelength division multiplexing (WDM) from a grating stabilized 975 nm laser diode (LD), which can provide up to 600 mW pump power. A polarization-independent optical isolator is used to ensure single direction oscillation. An LA-TFG is employed to induce polarization-dependent loss and polarization spectrum filtering. Two in-fiber polarization controllers (PC1 and PC2) are located before and after the LA-TFG. A 10:90 fiber coupler is placed after the EDF to tap 10% of laser power out of the cavity. The total cavity length including the EDF and all fiber pigtails of the used components is 2.7 m. The cavity net dispersion is ~0.004 ps$^2$. From the existing laser cavity, only Q-switch operation can be achieved. In order to realize mode-locking, a length of 150-m dispersion-shifted fiber (DSF) is incorporated into the cavity to increase the nonlinear effect. The DSF has a dispersion coefficient of ~5 ps$^2$/km. Then, the total cavity length becomes ~153.7 m, and the cavity net dispersion is ~0.75 ps$^2$. The output pulses were measured with 1-GHz photodetector and 2.5-GHz oscilloscope.

![Fig. 3. Spectra of single-wavelength (black dotted line at 1554.9 nm, blue dashed line at 1561 nm) and dual-wavelength (red solid line) Q-switched pulses.](image)
Firstly, Q-switching operation was achieved in the case of short cavity. The laser can operate on single- or dual-wavelength Q-switching once the pump power exceeds 275 mW, through adjusting the two PCs. Figure 3 shows the output spectra of the Q-switched pulses at the pump power 295 mW. The single-wavelength Q-switching operation can be switched between the two wavelengths: 1554.9 nm and 1561 nm. And the two simultaneous Q-switching lasing wavelengths for the dual-wavelength operation center at the same two wavelengths. The wavelength spacing is 6.1 nm. The operation wavelengths and wavelength spacing are coincident with the polarization spectrum characteristics of the used LA-TFG. Figure 4 shows the typical oscilloscope trace of single-wavelength Q-switched pulse. The full width at half maximum (FWHM) of the Q-switched pulse is 1.84 $\mu$s. The repetition rate of pulse is 175.7 kHz, corresponding to a pulse interval of 5.69 $\mu$s. Figure 5 shows the dual-wavelength Q-switched pulse train and its single pulse zoom-in. The FWHM is 1.86 $\mu$s, which is a little broader than that of single-wavelength case. The repetition rate of pulse is 217.9 kHz, corresponding to a pulse interval of 4.59 $\mu$s. The repetition rate difference between single- and dual-wavelength operations is attributed to the different polarization states. To investigate the dynamics of the Q-switched fiber laser, we increase the pump power while keeping the PCs unchanged. The positions and the wavelength separation of the two lasing peak do not depend on the pump power. A 1-nm bandpass tunable optical filter was used to resolve the dual-wavelength output. Pulse train at each wavelength has the same repetition rate as the total dual-wavelength Q-switched pulses.

Fig. 4. Typical Q-switched pulse train and single pulse zoom-in under single-wavelength operation.

Fig. 5. Dual-wavelength Q-switched pulse train and its single pulse zoom-in.

In the case of short cavity, mode-locking could not be obtained. We estimated it is because of too weak saturable absorption effect, since the LA-TFG has a relatively low PDL and short cavity leads to low nonlinearity. To overcome this problem, a length of 150-m DSF was incorporated into the laser cavity. In this case, the mode-locked pulses were obtained as the pump power was increased to 178 mW. Figure 6 presents the typical single-wavelength mode-locked spectra at 1554.8 nm with 0.65-nm bandwidth and 1560.9 nm with 0.43-nm bandwidth at 180 mW pump power. Then the single-wavelength mode-locking in the time domain was investigated by using a high-speed oscilloscope, as shown in Fig. 7. The pulse repetition rate is 1.32 MHz, which is determined by the cavity length. Notably, the pulse profile exhibits rectangular shape on the oscilloscope trace, as shown in Fig. 7(b). The pulse
duration is 120.1 ns. It was naturally expected that dual-wavelength passive mode-locking could be achieved as the Q-switch operation. After carefully tuning the two PCs, simultaneous mode-locking at two wavelengths could also be obtained. As can be seen from Fig. 8, the dual-wavelength simultaneously oscillated at 1554.8 and 1560.9 nm. Similar to the single-wavelength case, the pulse profile of dual-wavelength mode-locking also exhibits rectangular shape on the oscilloscope trace, as shown in Fig. 9. The pulse repetition rate is still 1.32 MHz. The difference with single-wavelength mode-locking is the broader pulse duration of 205.8 ns, as presented in Fig. 9(b).

Fig. 6. Switchable spectra of single-wavelength mode-locked pulses.

Fig. 7. Typical mode-locked pulse train and its single pulse zoom-in under single-wavelength operation.

Then the pulse evolution with the variation of the pump power was investigated under both single- and dual-wavelength cases. Figure 10(a) shows the single-wavelength pulse broadening when the pump power was increased. The pulse amplitude was almost clamped at a constant level during the pulse broadening. Figure 10(b) shows the experimentally measured pulse duration versus the pump power. As can be seen in Fig. 10(b), the pulse duration varied from 120.1 ns to 154.5 ns as the pump power was enhanced from 180 mW to 580 mW. The radio frequency (RF) spectrum presented in the inset of Fig. 10(b) exhibits an RF signal-to-noise ratio (SNR) over 80 dB, which indicates that the mode-locking pulse is stable under laboratory conditions. Similarly, the duration of the dual-wavelength mode-locked pulse varied from 205.8 ns to 259.1 ns with the pump power increased from 180 mW to 580 mW, with the pulse peak almost clamped at a constant level, as shown in Fig. 11. Figure 11(b) also shows the experimentally measured pulse energy versus the pump power. The pulse energy increased monotonically to 26.7 nJ when the pump power was up to 580 mW.
To further study the characteristics of the dual-wavelength mode-locking operation, a bandpass filter with a bandwidth of 1 nm was employed to resolve the lasing at each wavelength. The filtered pulse-trains oscillated at the two wavelengths suggest that the both two wavelengths operated simultaneously and individually in passive mode-locking state. The pulse profiles of the both two wavelengths are still rectangular, but with a little smaller pulse duration than that of dual-wavelength mode-locked pulse.

Fig. 10. (a) Single-wavelength pulse broadening with the pump power increased, (b) measured pulse width versus the pump power (the inset of is RF spectrum).

Fig. 11. (a) Dual-wavelength pulse broadening with the pump power increased, (b) measured pulse width and output pulse energy versus the pump power.
4. Conclusions

We have, for the first time to our best knowledge, proposed and demonstrated switchable dual-wavelength Q-switched and mode-locked fiber lasers by using an LA-TFG with unique polarization properties. Q-switched pulses were obtained in the case of short length cavity, while mode-locked pulses were only achieved in the case of long length cavity. Both Q-switching and mode-locking could be operated at switchable single wavelength and dual wavelength. Due to the peak-power clamping effect, the mode-locked laser radiates nanosecond rectangular pulses. The duration of the rectangular pulse broadens with the increasing pump power.

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